Acoustic reconstruction of music performance spaces using three-dimentional digital waveguide mesh models

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Abstract: The concept of auralisation and its importance in room acoustic simulation are briefly discussed and an overview is given of the various acoustic modelling techniques available. In particular, 3-D digital waveguide mesh physical modelling is discussed in more detail. It offers a number of implementation advantages and is deemed capable of meeting the accuracy requirements of Acoustic Reconstruction applications. A complete room acoustic modelling system is proposed, including a CAD front-end for room configuration.

Introduction

Room Acoustics is concerned with how the physical characteristics of a room (dimensions/shape/ surfaces) influence sound perception. For given positions of sound source and listener, this influence is fully described by the Room Impulse Response (*RIR*). The RIR can be used to synthesise the acoustic stimuli induced at the listener's ears by any given sound source. These can be listened to over headphones, in what is known as *auralisation* (figure 1).

Only recently has auralisation become a practical possibility, with the development of sophisticated RIR measurement techniques and advances in digital signal processing. Auralisation with measured RIR can be very useful (e.g in listening tests for concert hall subjective evaluation surveys, design and test of loudspeakers and sound diffusion systems) but is obviously restricted to the study of existing rooms. In Auditoria Design or Acoustic Reconstruction applications, the room under study does not actually exist. Methods of obtaining the RIR *directly* from a knowledge of its physical characteristics are therefore required.

Acoustic reconstruction is relevant to the fields of music history, musicology and ethno-musicology with obvious application in the context of authentic, or historically accurate musical performances, normally associated with the use of period instruments. The study of the inter-relationship between the evolution of the acoustics of music performance spaces and the development of musical styles and instruments over the centuries is another possible application.

Outside the musical/musicological sphere, the investigation of the acoustic behaviour of ancient buildings, particularly prehistoric structures, can contribute to a more complete understanding of their function and significance. Many archaeological sites, notably Mayan ruins and northern European megalithic monuments, feature striking acoustical phenomena.

Acoustic modelling and accuracy requirements

The problem of calculating a RIR amounts to solving the sound wave equation for a particular room under analysis. Because analytical solutions can be obtained only for very simple geometries and idealised boundary conditions, *acoustic models* have to be utilised. Analog modelling, based on indirect RIR measurement using ultra-sounds to excite a scale-model, is still very much in use. However, as in other fields of engineering, it is being gradually superseded by digital computer modelling based on numerical methods.

Models directly based on the wave equation are normally called *physical models*. Excessive computational loading has been their main drawback for room simulation. To circumvent this problem, simplified approaches to the analysis of sound propagation have been proposed, namely geometric models (*ray-tracing, mirror-image source method*) inspired by optics. In their standard formulations, reflection and absorption are the only modelled phenomena. Sound waves are treated like rays, based on the assumption that the room surfaces are relatively flat and their dimensions large when compared to the sound wavelength. This corresponds to the limiting case of very high frequencies. These simplifications allow relatively fast calculations but severely restrict the model's validity, making it largely dependent on the architectural details of the room.

In Auditoria Design, it is generally the case that before the acoustic behaviour of the building can be considered, many of its architectural features are already fixed. This, together with the fact that modern architecture does tend to favour large flat interior surfaces, is the main reason why software packages based on geometric modelling, although far from ideal, are considered acceptable.

In contrast, whenever absolute rather than comparative appreciation is intended, as is the case in the acoustic reconstruction of music performance spaces, approximate models are not suitable. Such applications call for the maximum possible level of accuracy, limited only by human auditory capabilities. Physical modelling is arguably the best approach in this context, since all wave propagation phenomena are taken into account.

3-D digital waveguide mesh modelling

Digital-waveguide mesh modelling was originally developed for musical applications. One- and two-dimensional versions have been successfully applied to sound synthesis and simulation of acoustic instruments.

Application to room acoustics requires 3-D meshes of suitably high density. The volume under analysis is spatially discretised as a grid of regularly spaced *nodes* interconnected by bidirectional *delay units*. Travelling waves can be simulated with this arrangement. Under the computation algorithm employed, the model implements a standard finite-difference time-domain approximation to the solution of the wave equation. *Air nodes* represent the propagation medium and can be assigned special functions, namely *mesh excitation* (modelling sound *sources*) and *sound output* (modelling *receivers*). *Boundary nodes* model the surfaces delimiting the space. Their scattering parameters vary according to the physical properties of the corresponding material.

Simulation is achieved by injecting an anechoic sound signal at a *source* node and recording the resulting acoustic pressure variation at the node(s) specified as receiver(s). The errors associated with the discretisation process, in particular frequency dispersion, can be reduced by increasing the density of the mesh.

Various 3-D mesh topologies have been proposed in the literature. Lossless models have been implemented using two of these topologies, illustrated in figure 2. Initial objective and subjective validation tests have confirmed their ability to accurately predict the low frequency room mode distribution and provide appropriate sound localisation cues.

Various model refinements are possible. For example, new techniques have recently been introduced to improve the dispersion error characteristics of the rectilinear mesh. It is also possible to model frequency-dependent air absorption using digital filters. These can be easily fitted into the waveguide mesh modelling framework – an important advantage. Integrated in boundary node transfer functions, they can also allow frequency and surface orientation dependent boundary conditions, making it possible to simulate the acoustic behaviour of surface materials more accurately. The total *RIR* computation time is given, in *s*, by

$$T_M = \left(\frac{1}{\alpha c}\right)^3 .V.RT_{60}.f_S^4 .t$$

where c is the medium's sound propagation speed (ms^{-1}); V is the volume of the room (m^3); RT_{60} is the reverberation time @ -60 *dB*; f_S is the audio sampling frequency (*Hz*); t is the average computation time per model node per iteration (*s*) and ± is an adimensional factor equal to 2 and $\sqrt{3}$ respectively for the rectilinear and tetrahedral meshes.

For example, it takes approximately 68*h* to obtain a 2*s* impulse response at 22050*Hz* for a room of 110.6m^3 using a rectilinear model running on the fastest single-processor platform tested. Tetrahedral models can be expected to be more than twice faster, but a typical music performance space can be hundreds of times larger and have longer RT_{60}. Moreover, in order to attain the desired level of perceptual accuracy it may be necessary to use higher f_S (i.e. denser meshes) and/or implement at least some of the model refinements mentioned before, only possible at the expense of t. Practical application to the study of real rooms therefore requires a very significant performance improvement. This seems achievable in the near future, as the models lend themselves extremely well to large-scale parallelisation. The results obtained so far indicate that the computational overhead due to communication between blocks operating in parallel is very low and, more importantly, can be made independent of their total number.

3-D CAD-based model configuration

A complete room acoustic simulation system is proposed in figure 3. Its main element (block 5) is the 3-D digital waveguide modelling program. Two ways of obtaining a digital representation of the room to be modelled can be employed. A commercial 3-D CAD package (block 2) provides a framework for regular-shaped rooms. However, it is impractical for rooms with irregular boundaries (e.g. pre-historic chambers), for which the ideal solution is an automatic spatial data acquisition system (block 1). Systems of this kind have been used in Archaeology as well as contemporary architectural and medical applications. In view of recent developments in precision portable laser scanners, it is likely that affordable, accurate systems for room interiors will become available in the near future.

An automated procedure to convert between the formats of CAD file and model mesh with user-defined meshing parameters (block 4) is currently being developed. It is based on the rasterisation of horizontal room 'slices' at regularly spaced elevations. The resulting 2-D node grids are then assembled into the appropriate 3-D format for physical modelling. It will be possible to extract the information directly from files produced by commercial 3D CAD software packages. It may be necessary to go through an additional stage of drawing preparation (block 3), to make sure an enclosed space is correctly defined, with all its boundaries characterised acoustically, and to position sound source(s) and receiver(s).

Summary and Future Work

3-D waveguide mesh models can provide accurate auralisation as required for the acoustic reconstruction of music performance spaces. Their practical applicability is currently restricted to very small-sized rooms but can be significantly extended in the near future by a combination of mesh topology optimisation, introduction of new algorithm refinements and large-scale parallelisation. A crucial element in this process is the development of a general tool for model validation reliant upon accurate 3-D surveys and *in situ* experimental measurements. For this purpose, an automated mesh configuration procedure using data from standard 3-D CAD models is being developed. This will allow easy integration of data from advanced room surveying techniques, for example laser scanning. Model validation case studies are being selected among English Heritage historic sites in Yorkshire, such as Helmsley Castle

Throughout much of the current work in archaeology, concerning computer visualisation of buildings, there have been strong emphases on finding methods to achieve the most photorealistic representations possible. Whilst GIS enables landscape data to be rigorously explored, the built structure itself remains a relatively underused resource. An holistic reconstruction, therefore, might contain a building's acoustic properties and character in addition to its visual properties and therefore help to reveal alternative interpretations of its form and structure. Experimental archaeology has explored the acoustic properties of buildings bit is obviously not applicable to the virtual structure and moreover, does not generate the kind of data necessary for the generation of computer-generated sound models.

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Figures

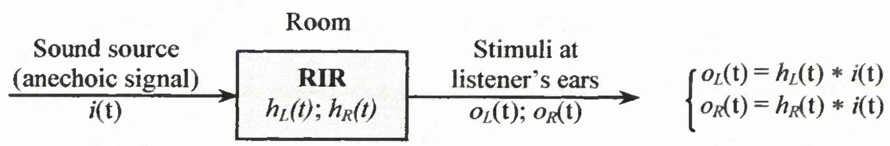

Figure 1. Auralisation ['' represents convolution; $h_L(t)$ and $h_R(t)$ stand for left and right ear RIR, respectively]*

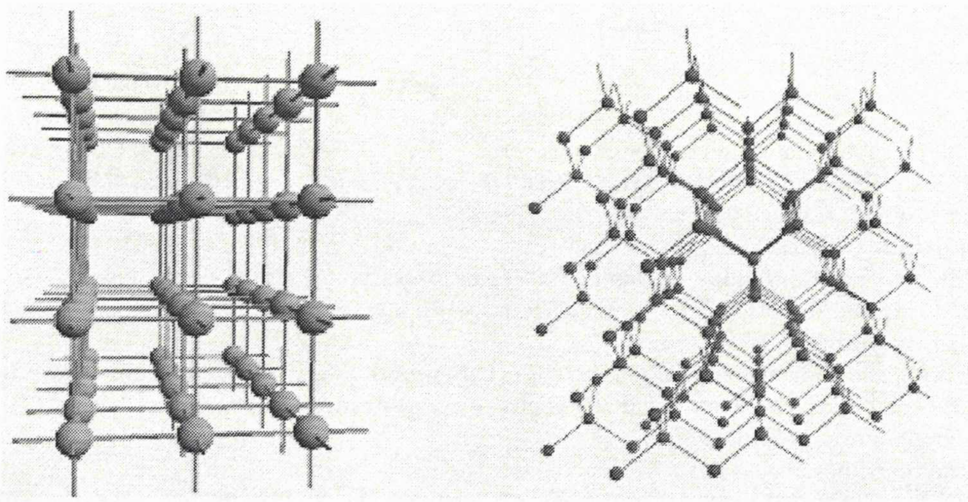

Figure 2. 3-D mesh topologies: Rectilinear (left) and tetrahedral (right)

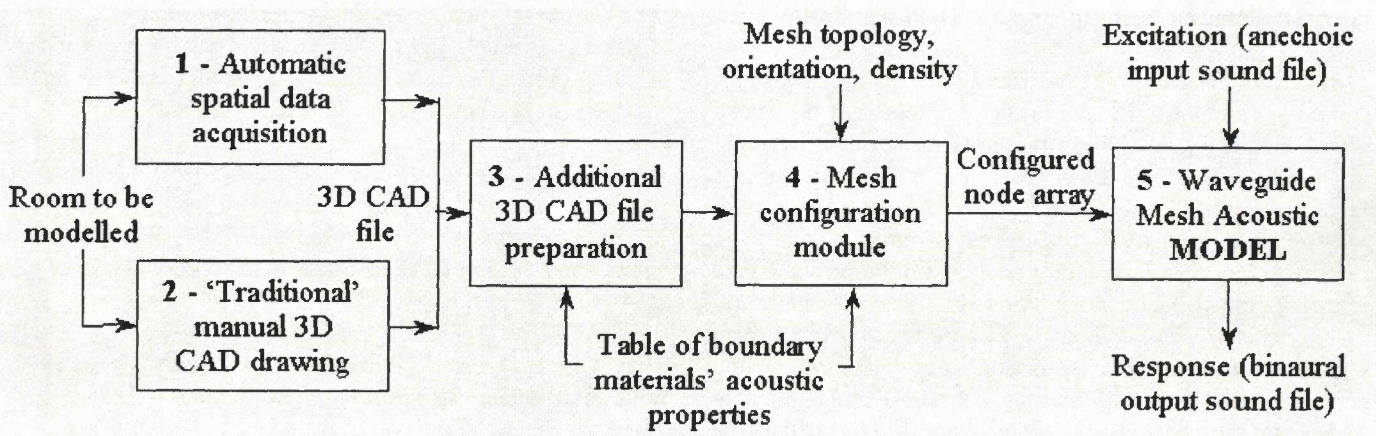

Figure 3. A 3-D waveguide-mesh modelling package with 3-D CAD front-end for room definition